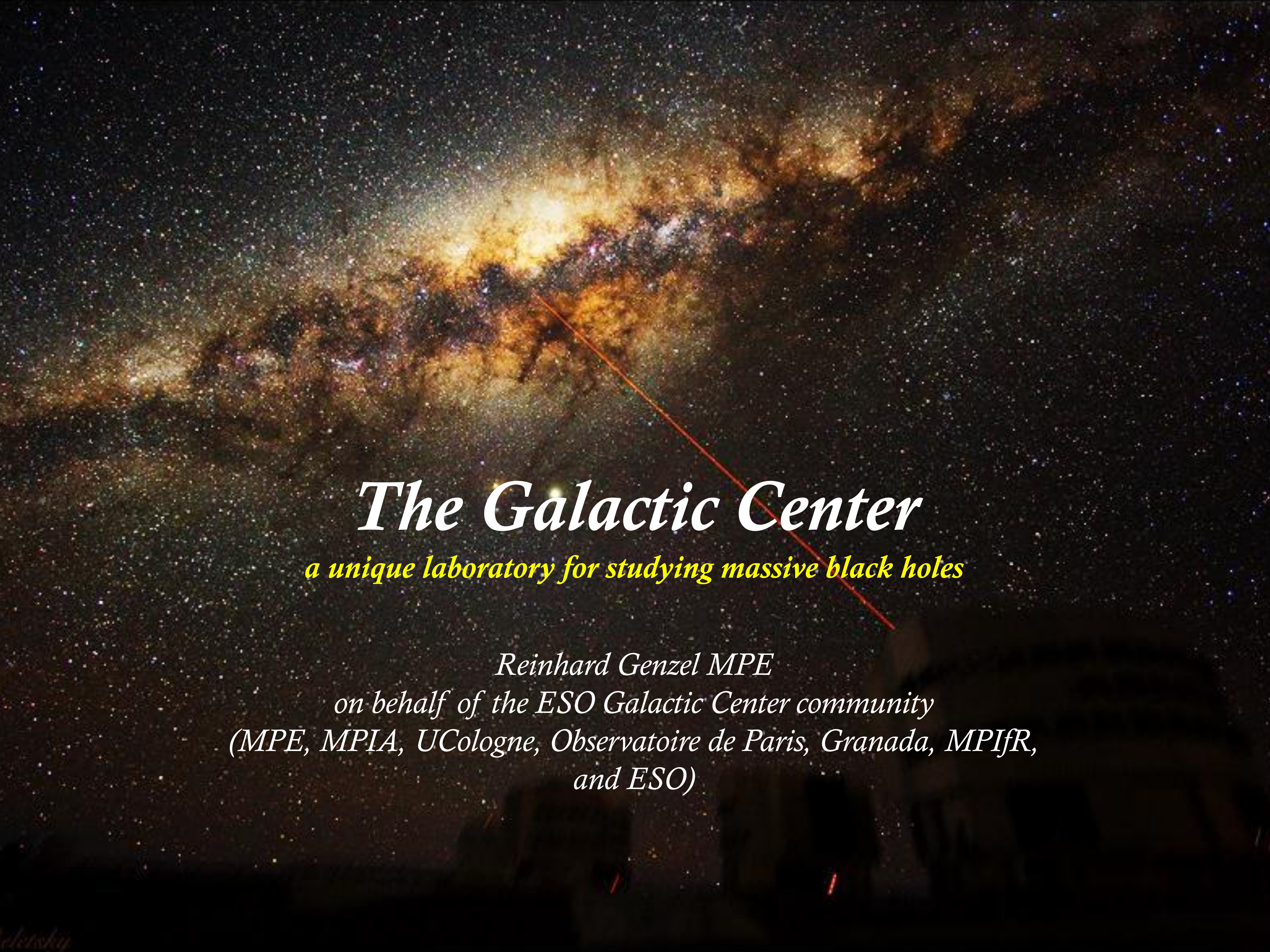


The Galactic Center

a unique laboratory for studying massive black holes

Reinhard Genzel MPE
on behalf of the ESO Galactic Center community
(MPE, MPIA, UCologne, Observatoire de Paris, Granada, MPIfR, and ESO)

Mon. Not. R. astr. Soc. (1971) **152**, 461–475.

ON QUASARS, DUST AND THE GALACTIC CENTRE

D. Lynden-Bell and M. J. Rees

(Received 1971 January 5)

SUMMARY

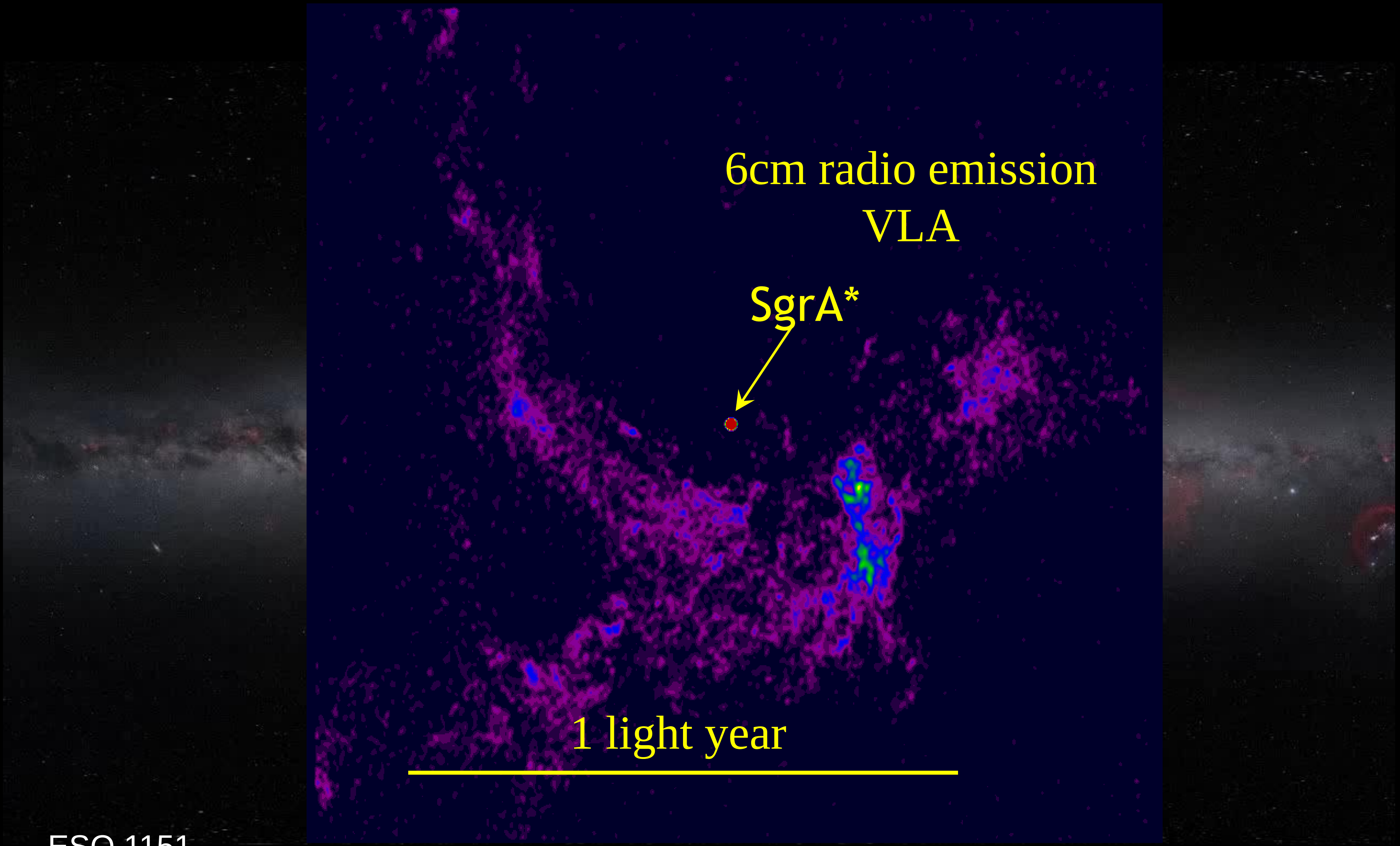
The black-hole model of galactic nuclei is used to discuss properties of quasars as proto-black-holes in the middle of galaxies. Quasar life-times may be as long as $\sim 10^8$ years and masses will be of the order of $10^8 M_\odot$. Dust in the neighbourhood of black holes is sometimes driven from the accreted gas by radiation pressure. This may cause the dust often seen in exploding nuclei and the infra-red radiation from the galactic centre. Dust models for the galactic centre are considered in detail, and it is suggested that there may be a central black hole currently emitting $\sim 1{\cdot}5 \times 10^8 L_\odot$ in the ultra-violet and blowing away a hot nuclear wind. Emission knots in the central regions probably contain prominent OB stars which would make the Galaxy later than Sb. Finally we list critical observations which could establish the existence of a large central mass in the Galaxy of so small a size that it must be associated with a black hole.

critical observations:

- emission line widths
- VLBI
- infrared emission/variability

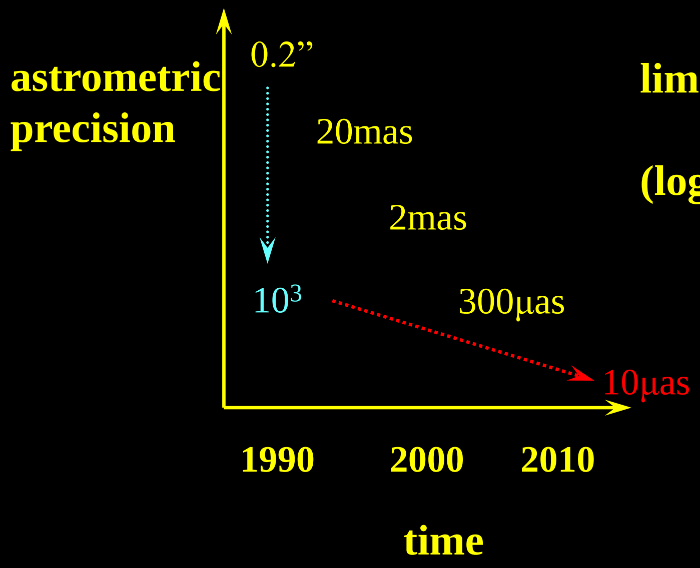
an unambiguous 'proof' for the existence of a black hole requires the determination of the gravitational field/space time metric to the scale of the event horizon.

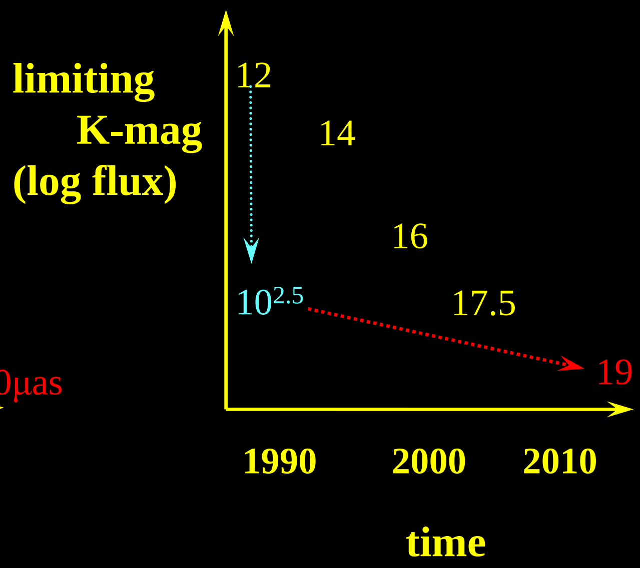
A Journey to the Center of the Milky Way



ESO 1151

2 decades of progress in high resolution IR imaging & precision astrometry





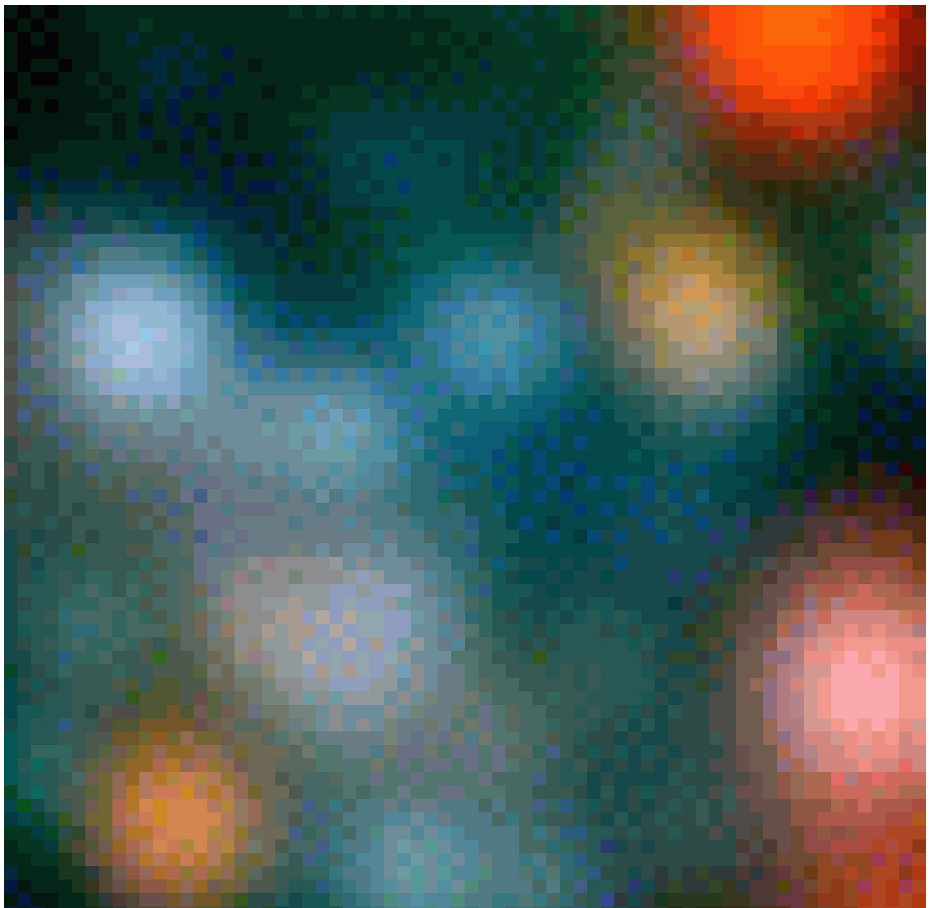
DePoy & Sharp 1991, Eckart et al. 1993, 1995, Genzel et al. 2003, Ghez et al. 2005

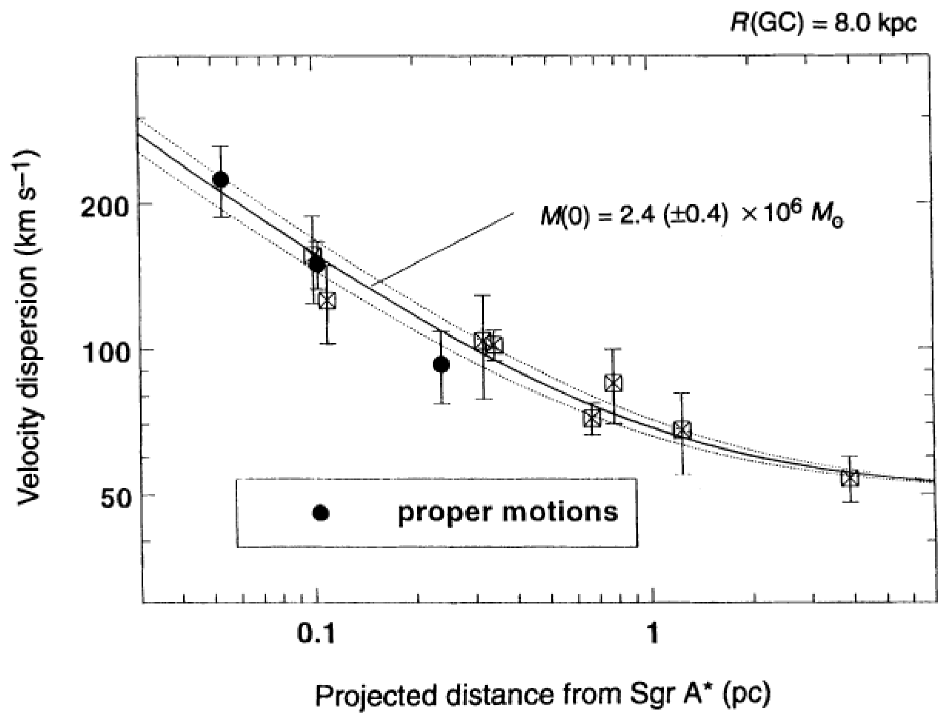
Observations of stellar proper motions near the Galactic Centre

A. Eckart & R. Genzel Nature 383, 1996

(1991-2001: courtesy of Harry van der Laan)

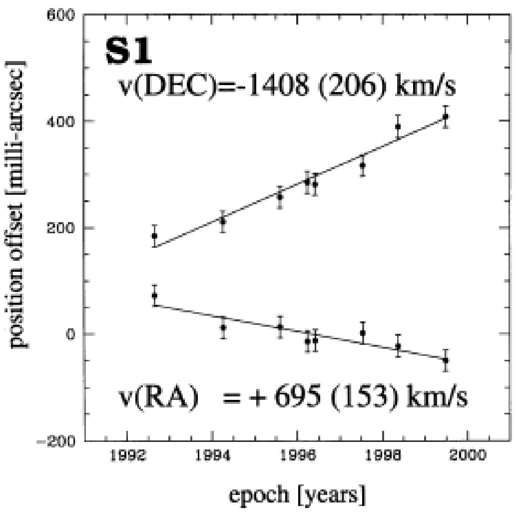
SHARP @ NTT

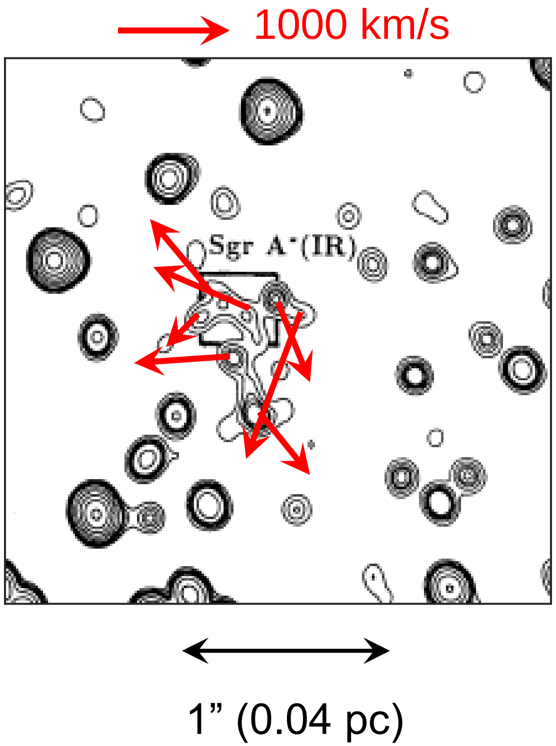


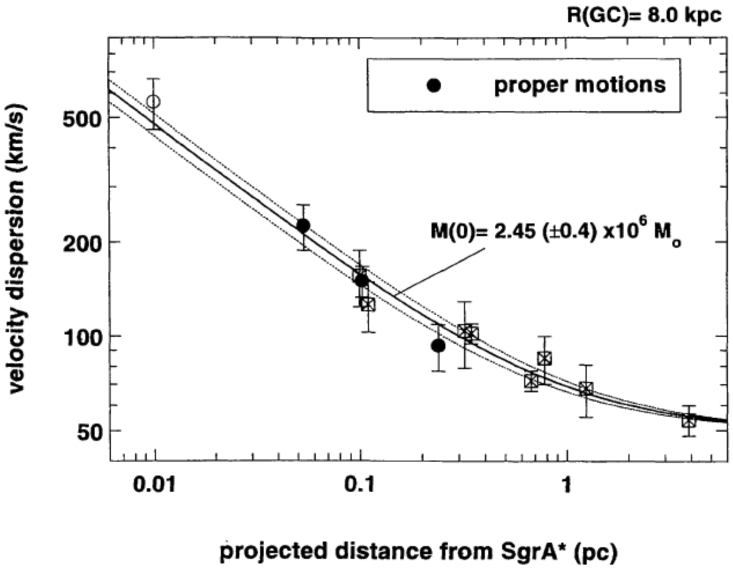


$$\boxed{\rho_\bullet > 10^{9.7} M_\odot pc^{-3}}$$

Should not be there: B-stars in the central light days with proper motions $>10^3$ km/s







$$\rho_{\bullet} > 10^{12} M_{\odot} pc^{-3}$$

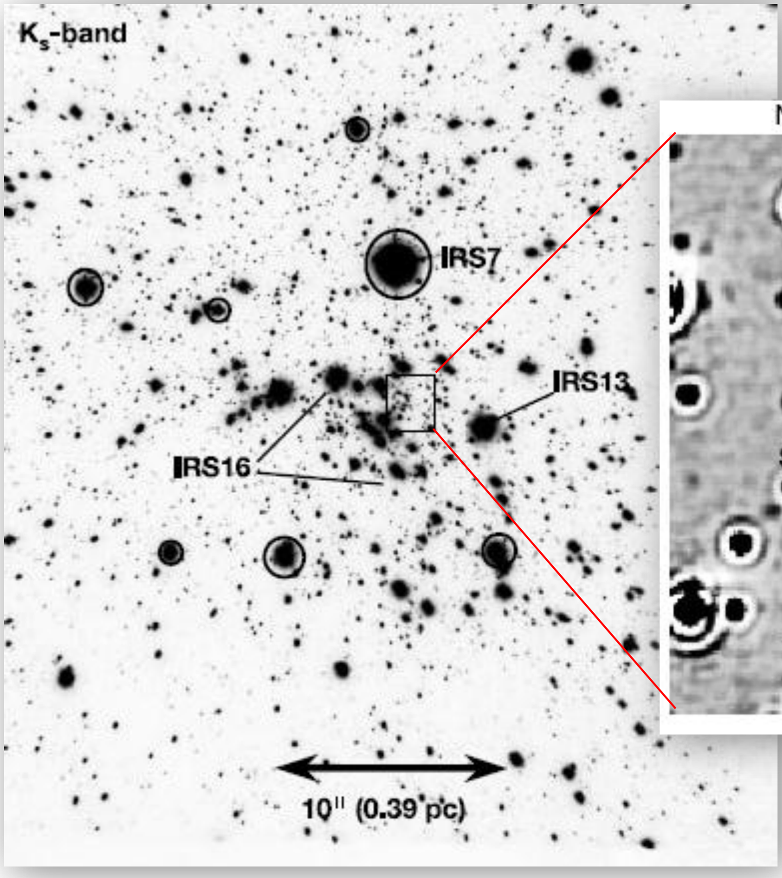
Eckart & Genzel 1997, Genzel et al. 1997

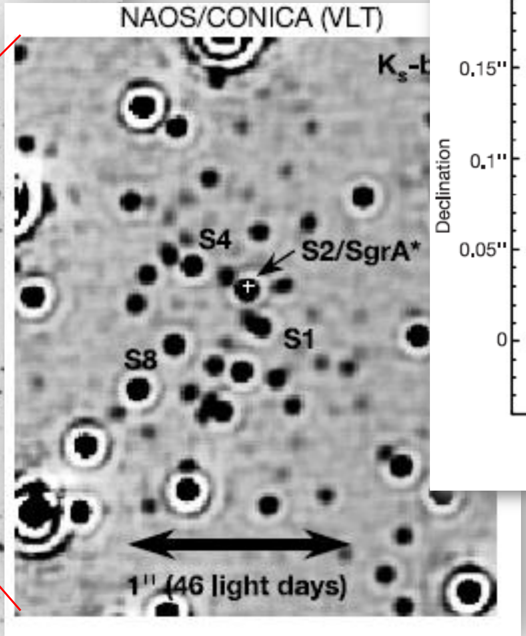
A star in a 15.2-year orbit around the supermassive black hole at the centre of the Milky Way

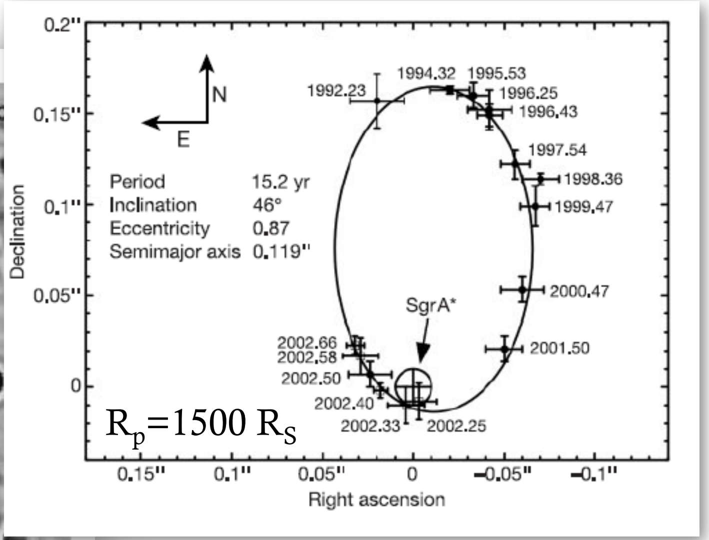
R. Schödel*, T. Ott*, R. Genzel*†, R. Hofmann*, M. Lehnert*, A. Eckart‡, N. Mouawad‡, T. Alexander§, M. J. Reid||, R. Lenzen¶, M. Hartung¶, F. Lacombe#, D. Rouan#, E. Gendron#, G. Rousset☆, A.-M. Lagrange**, W. Brandner††, N. Ageorges††, C. Lidman††, A. F. M. Moorwood††, J. Spyromilio††, N. Hubin†† & K. M. Menten‡‡

Nature 419, 2002

NACO@VLT



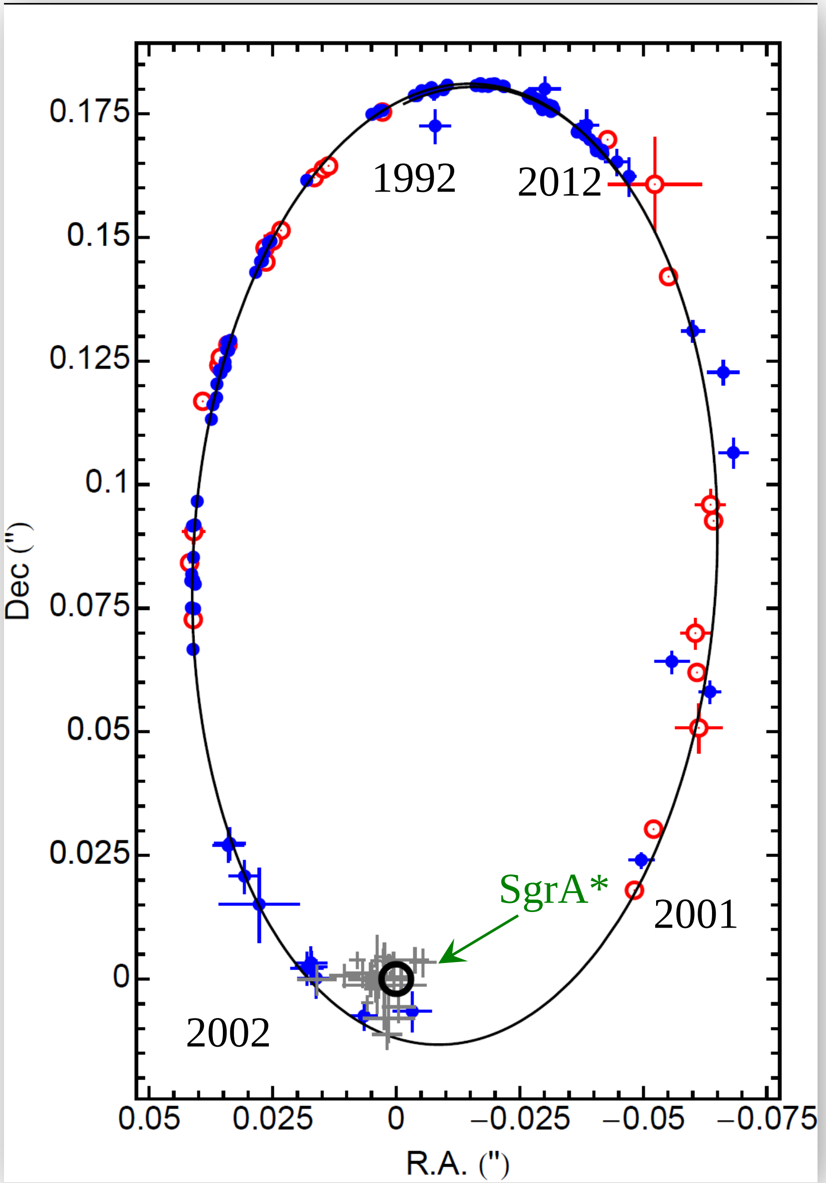




$$\rho_{\bullet} > 10^{16} M_{\odot} pc^{-3}$$

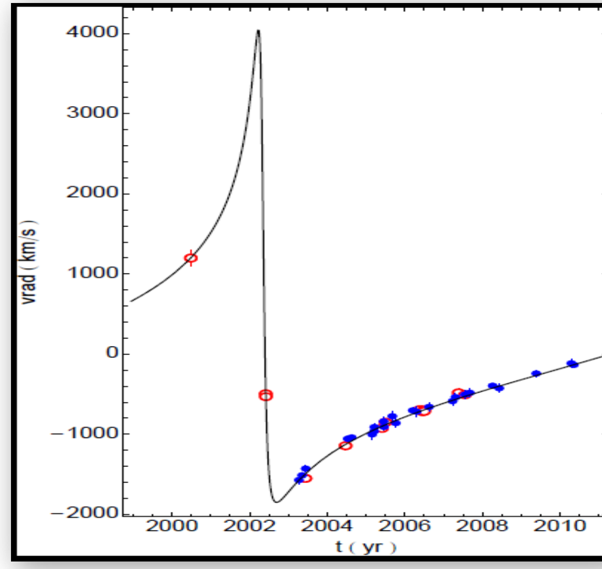
see also Ghez et al. 2003

Once around: S2 (1992-2012)



Ghez et al. 2008, Gillessen et al. 2009a,b

SINFONI + NACO @ VLT

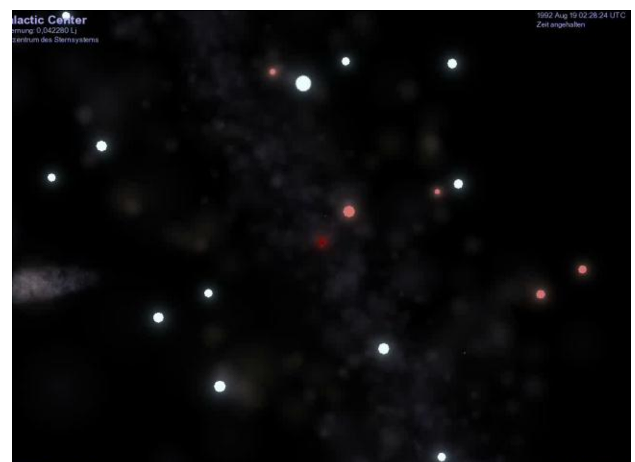


$M_\bullet = 4.30(\pm0.20)_{stat}(\pm0.30)_{sys}\ x10^6\ M_\odot$

$R_0 = 8.28\ (\pm0.15)_{stat}(\pm0.29)_{sys}$ kpc

$\rho_\bullet > 10^{19.5}\ M_\odot pc^{-3}$

$M_{extended}/M_\bullet <$ a few 10^{-2}

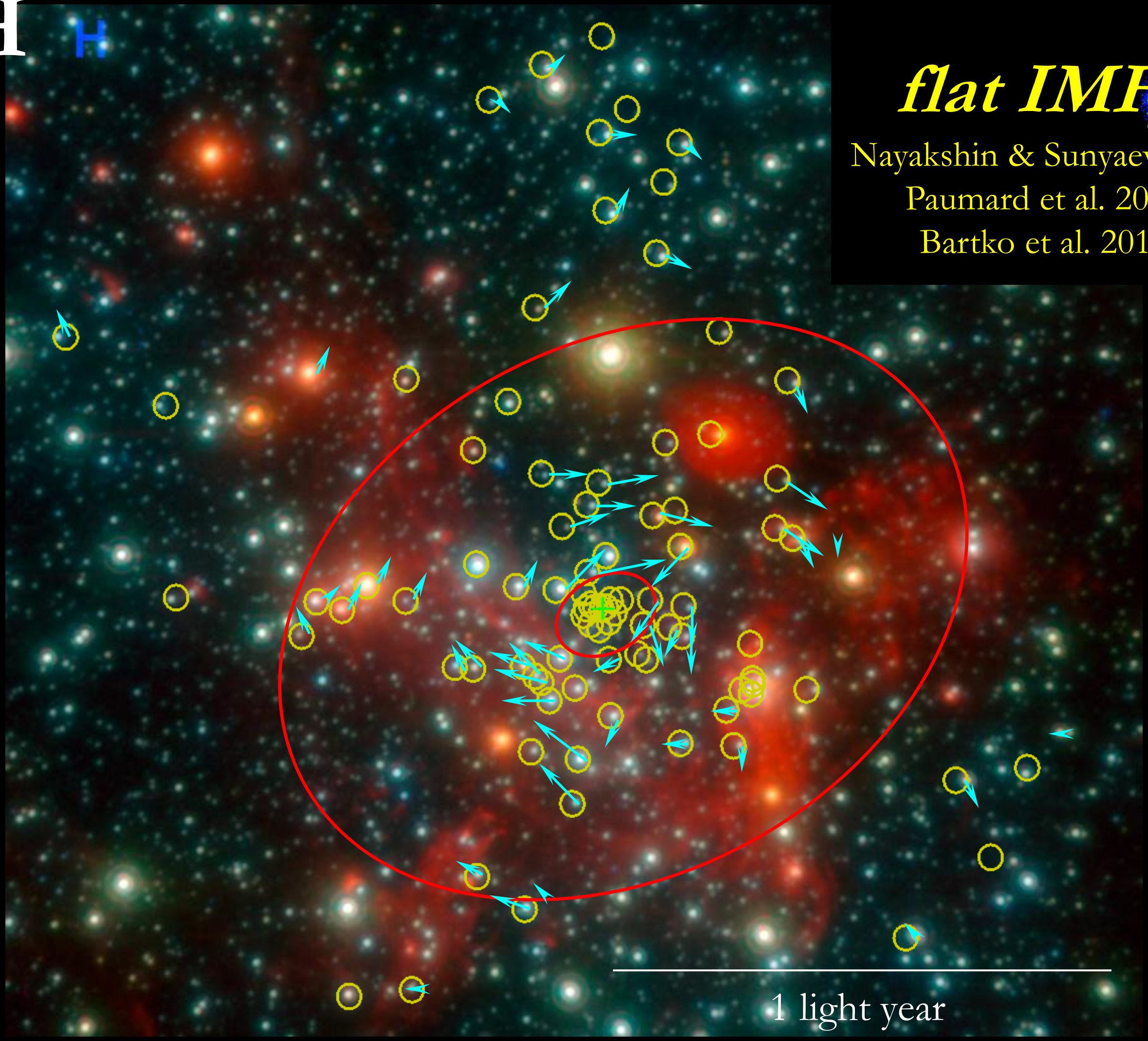


The environment of a massive black hole

key theoretical predictions:

- star formation near BH very difficult if not impossible
- power-law cusp of old stars & remnants centered on BH
- $L_{SgrA*} \sim 10^{8-9}\ L_{\odot}$
- binaries on loss cone orbits get captured with one member ejected out of Galaxy

Young massive stars near the BH

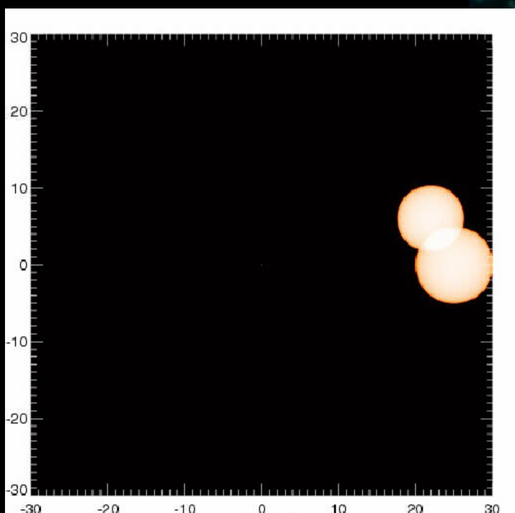


flat IMF !

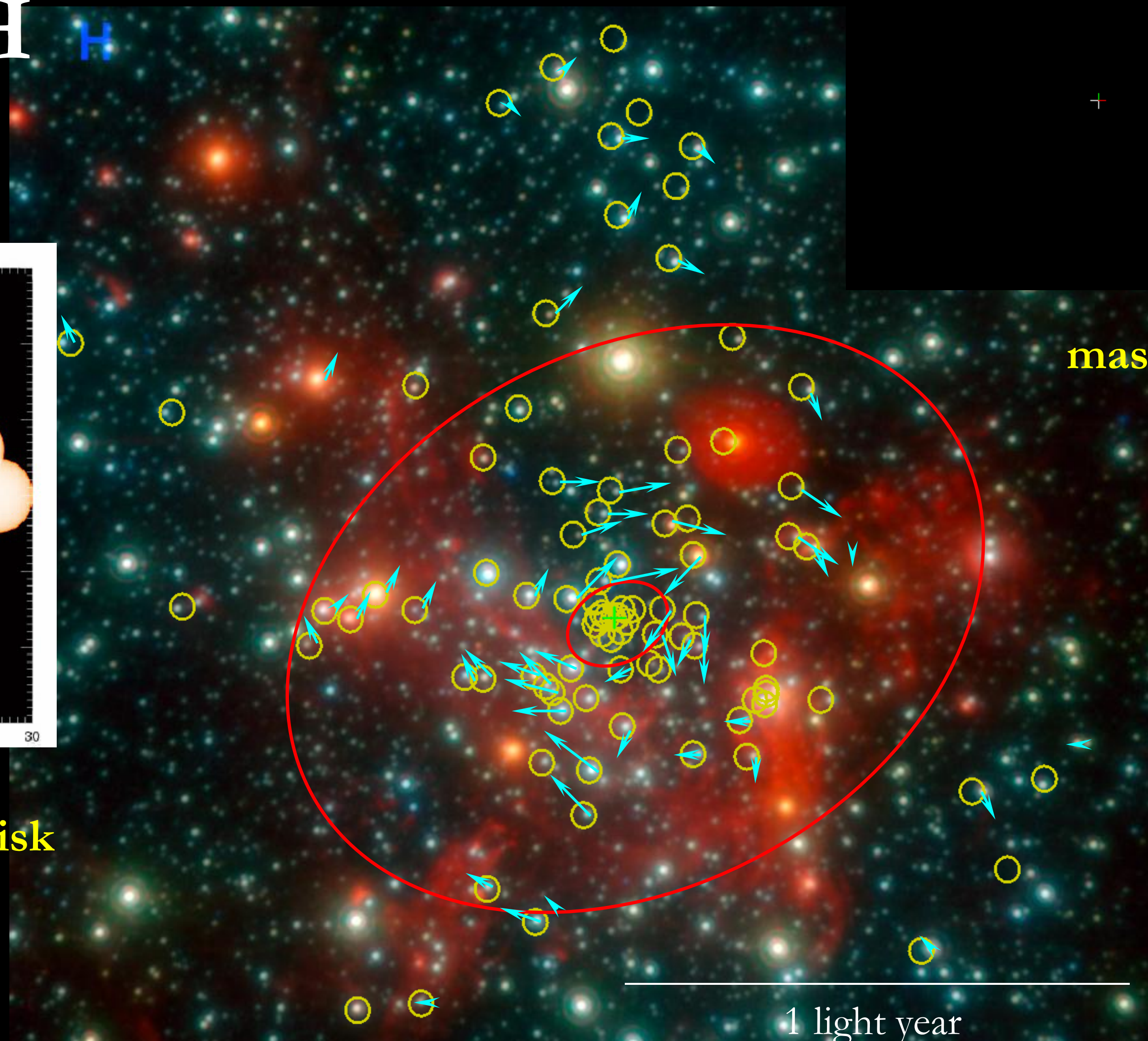
Nayakshin & Sunyaev 2005
Paumard et al. 2006
Bartko et al. 2010

Allen et al. 1990, Forrest et al. 1987, Krabbe et al. 1991, 1995, Gerhard 2001, Levin & Beloborodov 2003, Genzel et al. 2003, Kim et al. 2003, Portegies Zwart et al. 2003. 2004, Guerkan et al. 2005, Paumard et al. 2006, Martins et al. 2007, Alexander et al. 2007, Yu, Lu & Lin 2007, Lu et al. astro-ph 2008 0808.3818, Bartko et al. 2008, astro-ph 0811.3903 , Hobbs & Nayakshin 2008 atsro-ph 0809.3752, Bonnell & Rice 2008 Science 321, 1060

Young massive stars near the BH



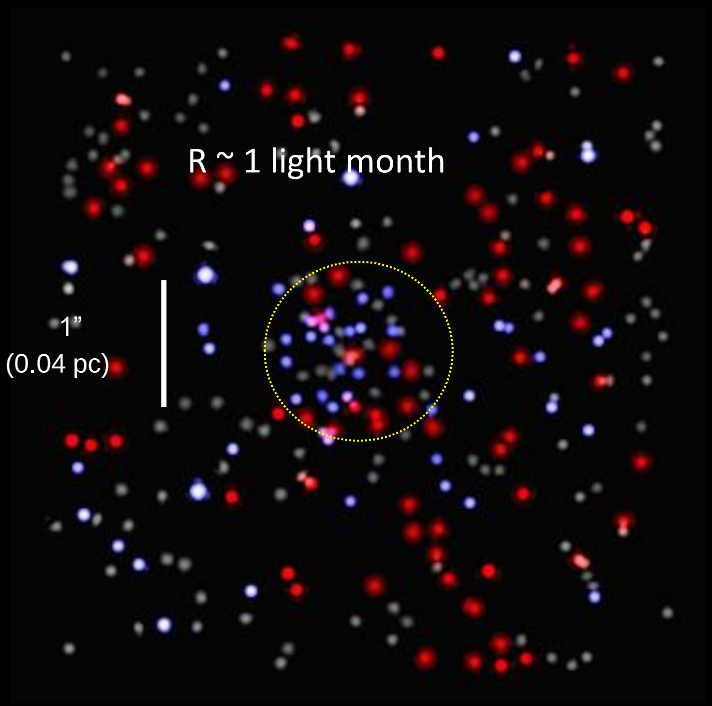
gas inflow &
in situ formation in disk

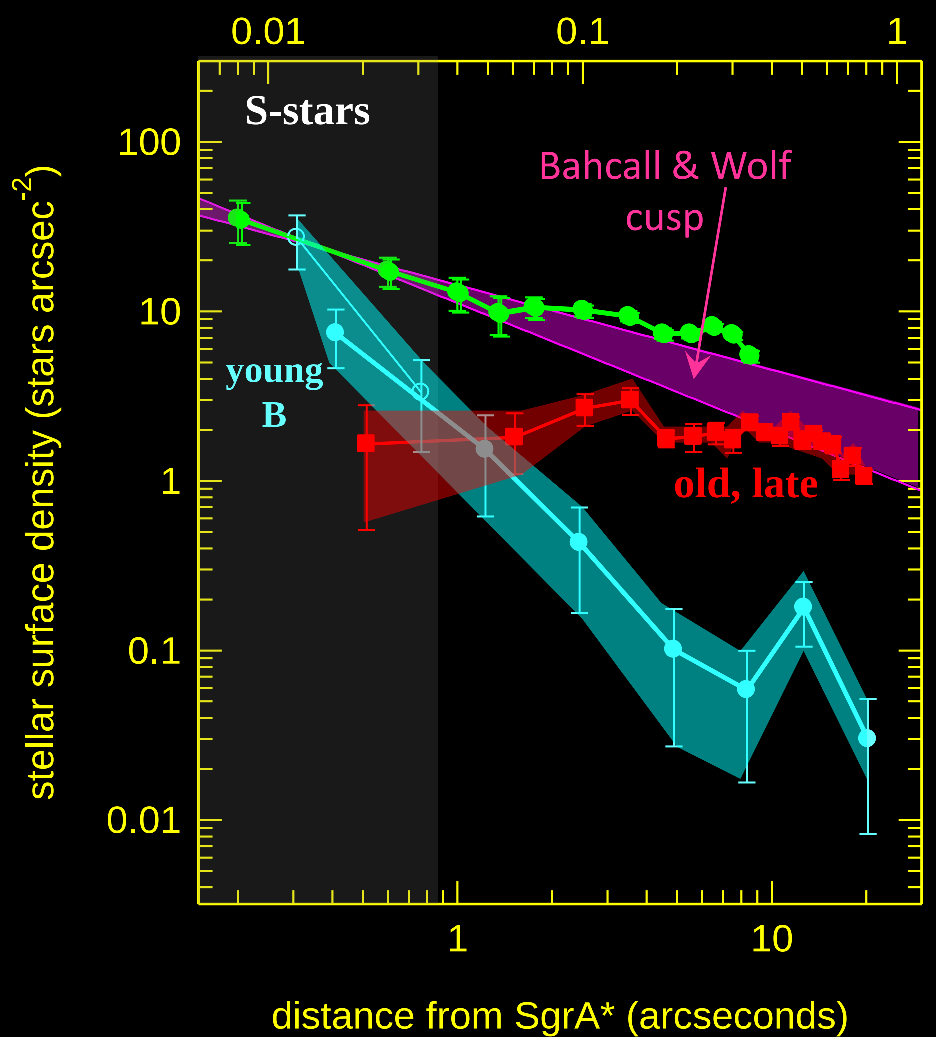


massive cluster
inspiral

Allen et al. 1990, Forrest et al. 1987, Krabbe et al. 1991, 1995, Gerhard 2001, Levin & Beloborodov 2003, Genzel et al. 2003, Kim et al. 2003, Portegies Zwart et al. 2003. 2004, Guerkan et al. 2005, Paumard et al. 2006, Martins et al. 2007, Alexander et al. 2007, Yu, Lu & Lin 2007, Lu et al. astro-ph 2008 0808.3818, Bartko et al. 2008, astro-ph 0811.3903 , Hobbs & Nayakshin 2008 atsro-ph 0809.3752, Bonnell & Rice 2008 Science 321, 1060

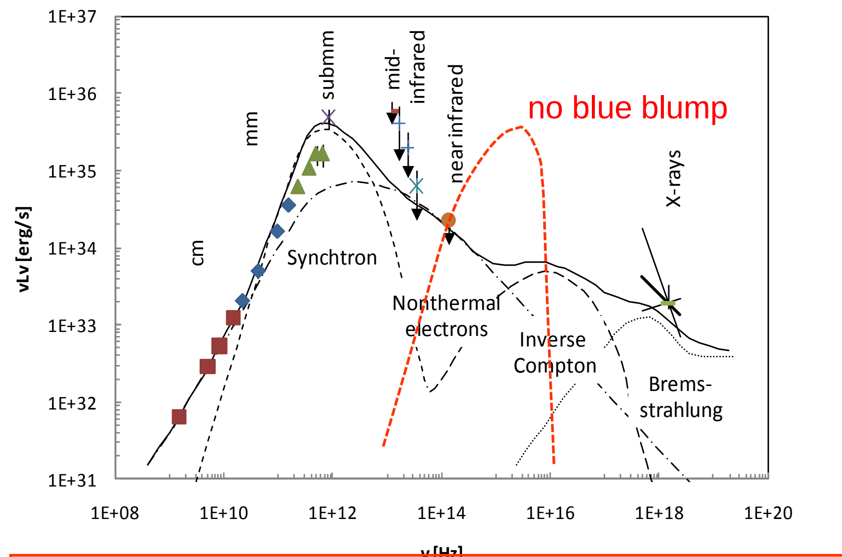
Where is the stellar cusp?





Bahcall & Wolf 1976, Genzel et al.1996, 2003, Eisenhauer et al. 2005, Schödel et al. 2007, Bartko et al. 2009b, Buchholz et al. 2009, Do et al. 2009, Dale et al. 2009, Alexander 2005, Merritt 2006, 2009, Dale et al. 2009, Davies 2010

Why is SgrA* so faint ?



$L_{SgrA*} \sim 10^{35\text{-}36}$ erg/s ~ 10^{-8} L_{edd}, $\eta_{radiation} \sim 10^{-6}$

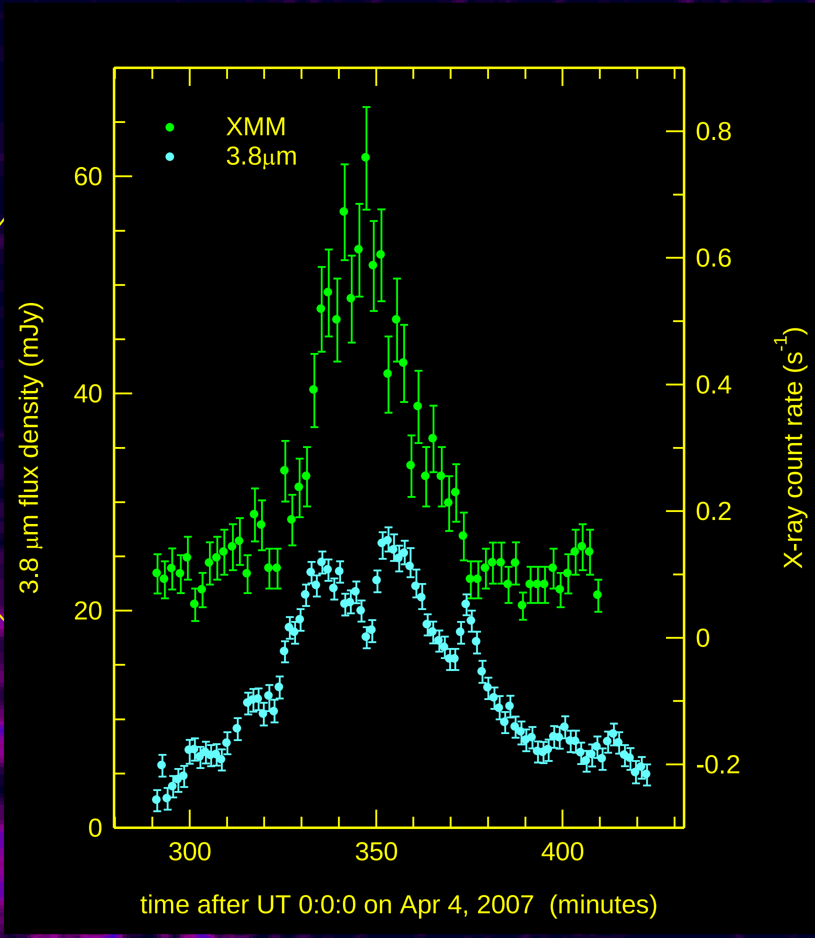
VLA radio image

Baganoff et al. 2001, Genzel et al. 2003 Nature 425, Ghez et al. 2004, Eckart et al. 2006, Dodds-Eden et al. 2009

Why is SgrA* so faint ?

low L/L_{Edd} is a combination of:

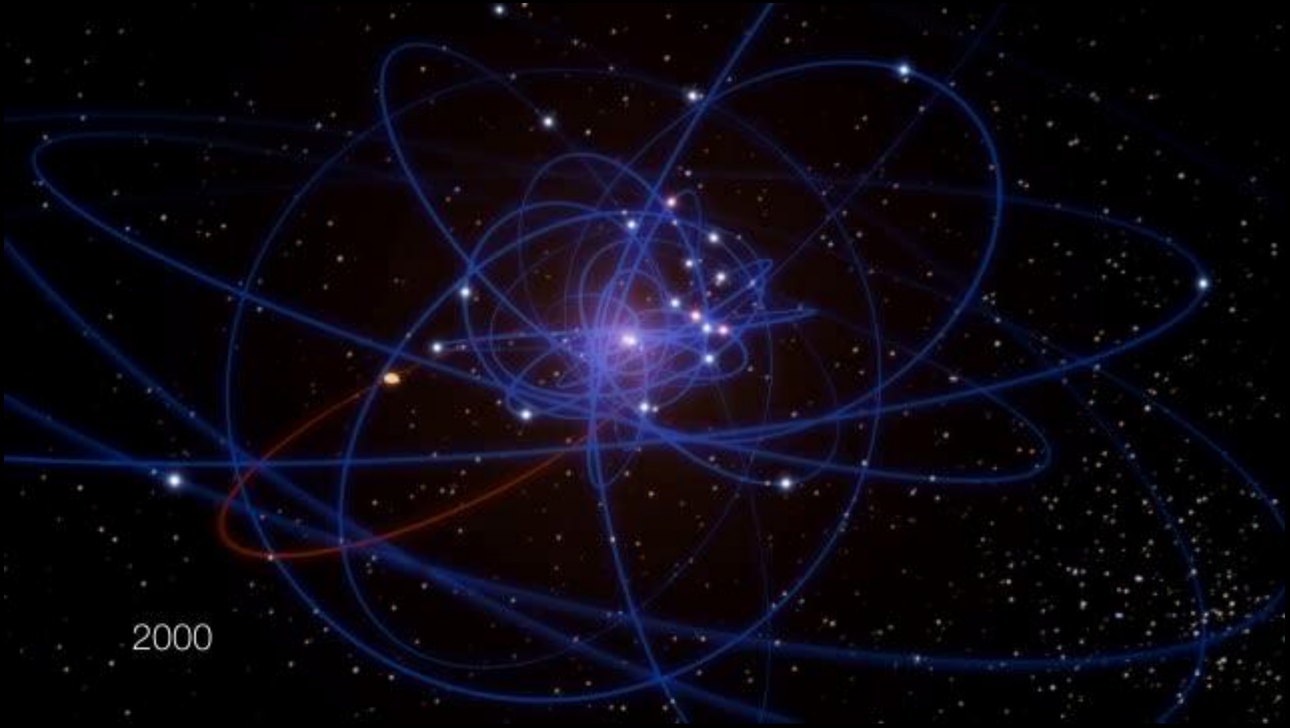
- low accretion rate at Bondi radius
- low efficiency angular momentum transport
- most of the gas arriving at a few R_s ejected back out



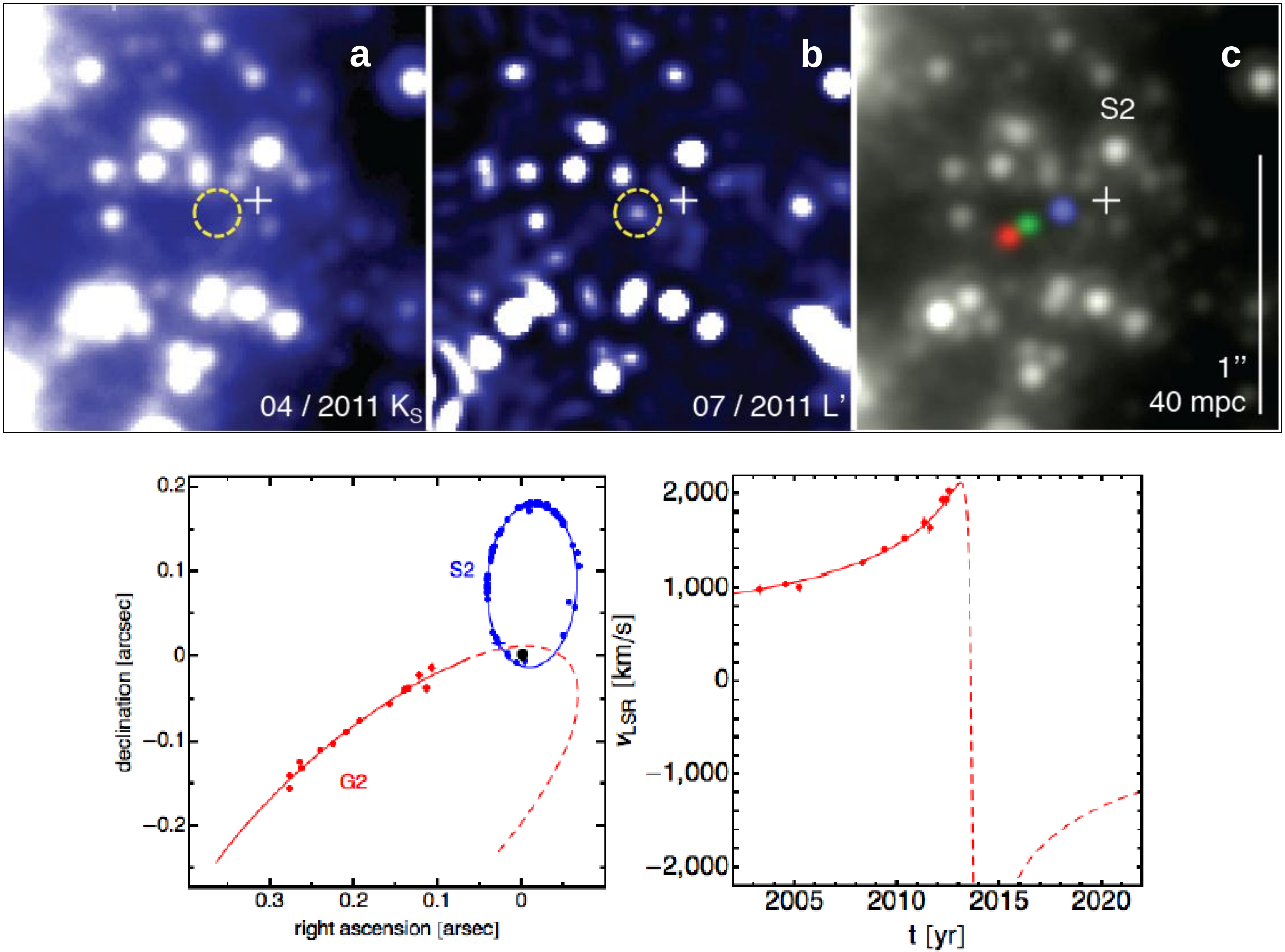
VLA radio image

Baganoff et al. 2001, Genzel et al. 2003 Nature 425, Ghez et al. 2004, Eckart et al. 2006, Dodds-Eden et al. 2009

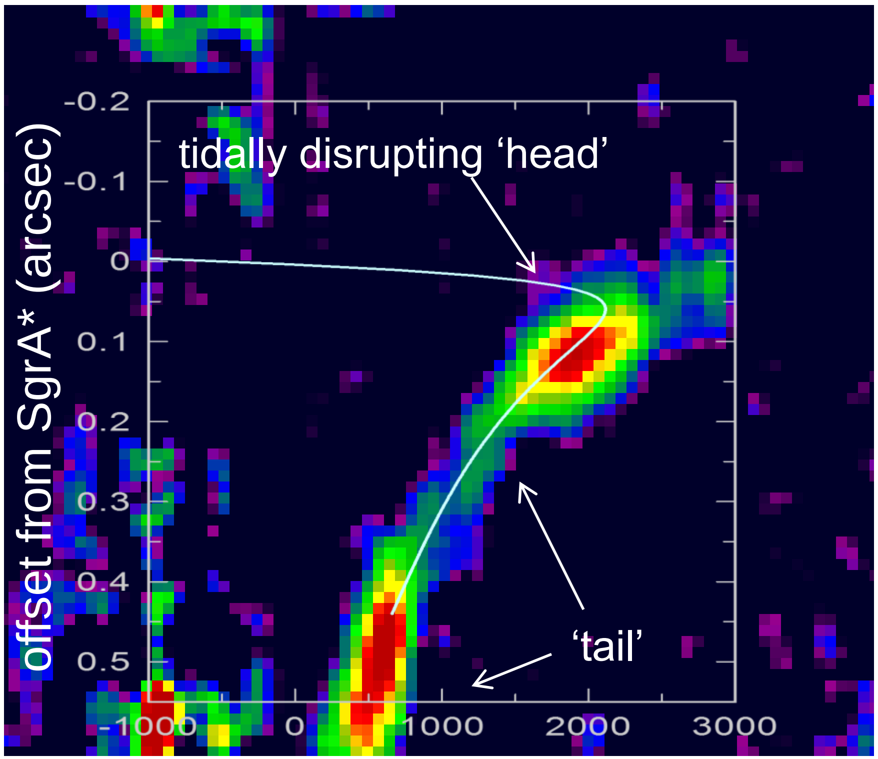
Yet another surprise: a gas cloud falling straight into the hole



Gillessen et al. Nature 481, 2012, stimulating: Burkert et al. 2012, Schartmann et al. 2012, Murray-Clay & Loeb 2012, Miralda-Escude 2012, Meyer & Meyer-Hofmeister 2012, Moscibrodzka et al. 2012


a
b
c
S2
04 / 2011 KS
07 / 2011 L’
1”
40 mpc
S2
G2
declination [arcsec]
right ascension [arsec]
0.2
0.1
0
−0.1
−0.2
0.3
0.2
0.1
0
vLSR [km/s]
2,000
1,000
0
−1,000
−2,000
2005
2010
2015
2020
t [yr]

2012 VLT Observations



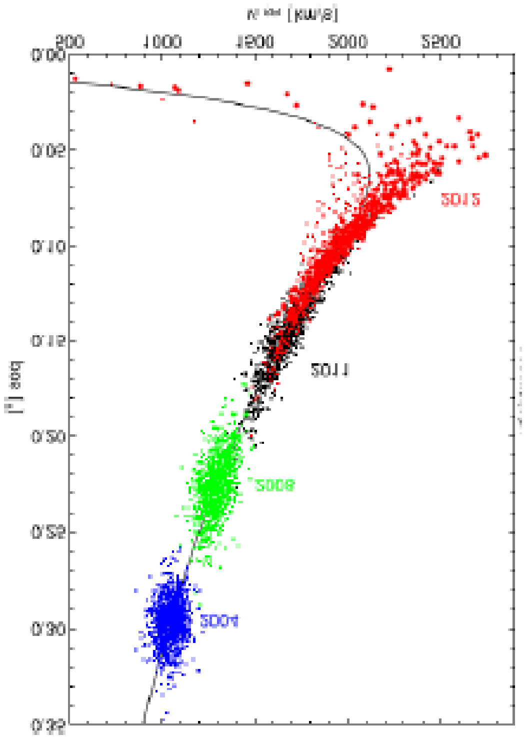
radial velocity (km/s)

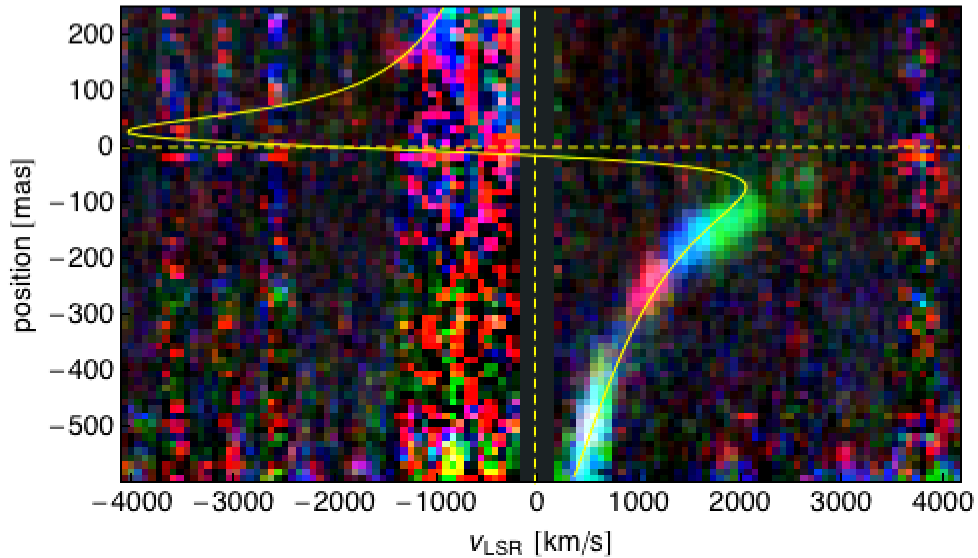
t_{int}~12 hr SINFONI+LGSF H+K
co-add Brγ, HeI, Pα

	Orbit fit
semi major axis (mas)………	666 ± 39
Eccentricity……………………	0.9664 ± 0.0026
inclination [°]…………………	109.48 ± 0.81
position angle of ascending node [°]………………………	95.8 ± 1.1
longitude of periastron [°]….	108.50 ± 0.74
epoch of periastron [yr]……	2013.69 ± 0.04
orbital period [yr]…………..	198 ± 18
$R(peri)/R_S$ …………	2200

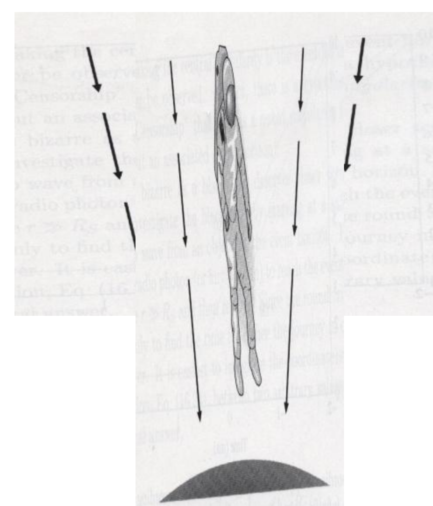
Gillessen et al. 2012b astro-ph 1209.2272

A perfect example of ‘spaghetti-fication’



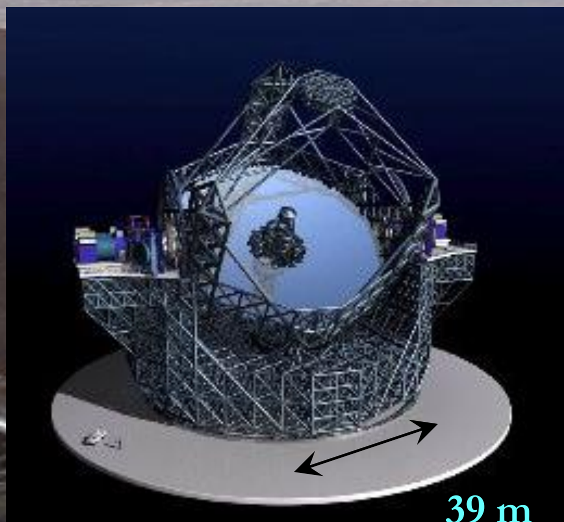


Simulation of tidal disruption on a ballistic orbit



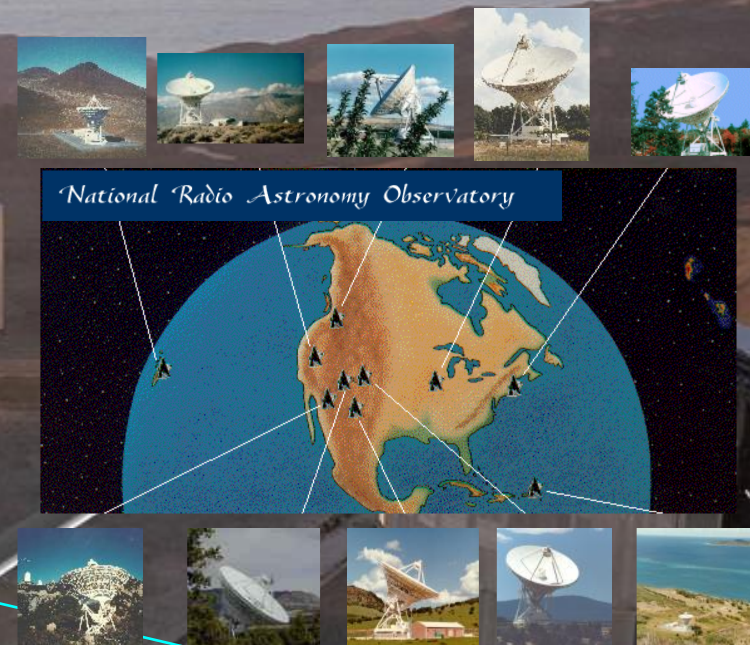
Gillessen et al. 2012b astro-ph 1209.2272

the future: zooming in on the horizon



EELT

200m



(sub)-millimeter
Very Long Baseline Interferometry
('Event Horizon Telescope')
(Doeleman et al. 2011)

'GRAVITY' experiment
(Eisenhauer et al. 2006, 2010)
near-IR precision interferometric astrometry
(10µarcsec~R_s, K_s<19)

ESO-VLTI